NASA Technical Memorandum 106763

IN-23
19P

Evaluation of PS 212 Coatings Under Boundary Lubrication Conditions With an Ester-Based Oil to 300 °C

Harold E. Sliney
Aerospace Design & Fabrication, Inc.
Brook Park, Ohio

William R. Loomis and Christopher DellaCorte
Lewis Research Center
Cleveland, Ohio

Prepared for the
International Conference on Metallurgical Coatings and Thin Films
sponsored by the American Vacuum Society
San Diego, California, April 24–25, 1995

National Aeronautics and
Space Administration

EVALUATION OF PS 212 COATINGS UNDER BOUNDARY LUBRICATION CONDITIONS WITH AN ESTER-BASED OIL TO 300 °C

Harold E. Sliney
Aerospace Design & Fabrication, Inc.
Brook Park, Ohio 44142

and

William R. Loomis and Christopher DellaCorte
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

High friction and wear of turbine engine components occur during high temperature excursions above the oxidation threshold of the liquid lubricant. This paper reports on research to study the use of a high temperature self lubricating coating, PS 212 for back-up lubrication in the event of failure of the liquid lubricant. Pin on disk tests were performed under dry and boundary-lubricated conditions at disk temperatures up to 300 °C. The liquid lubricant was a formulated polyol ester qualified under MIL L-23699. At test temperatures above the oil's thermal degradation level, the use of PS212 reduced wear, providing a back-up lubricant effect.

INTRODUCTION

High friction and wear of turbine engine components occur during high temperature excursions above the oxidation threshold of the liquid lubricant. A possible solution to this problem is the use of thermally stable solid lubricant coatings for back-up lubrication. A plasma sprayed solid lubricant coating composition (PS 212) developed at NASA, Lewis Research Center is considered a promising candidate for this application. It has been shown that this coating is an effective lubricant under many sliding conditions including temperatures well above the decomposition temperatures of synthetic oils (refs. 1 and 2). It has also been reported to exhibit very low wear rates on components of internal combustion engines where the components are exposed to fuel and oil vapors and hot exhaust gases. For example, PS 212 coatings solved a wear problem with a sliding contact port seal in an experimental Rotorcam engine (ref. 3).

Therefore, this program was initiated to evaluate PS 212 as a back-up lubricant for boundary lubricated metals. Pin on disk tests were performed under dry and boundary lubricated conditions at disk temperatures up to 300 °C. The liquid lubricant was a formulated polyol ester qualified under the military specification MIL L-23699, (ref. 4). The material combinations evaluated were: M50 pins on PS 212-coated disks, Stellite 6B pins on PS 212-coated disks, and baseline test combinations of M50 on M50 and 6B on Inconel X-750.

EXPERIMENTAL MATERIALS

Lubricants

The liquid lubricant is a fully formulated polyol ester qualified under the military specification, MIL L-23699C (ref. 4). Important viscometric requirements are: a minimum viscosity of 5cS at 99 °C and 25cS at 38 °C, and a maximum viscosity of 13 000cS at -40 °C. The maximum acceptable pour point is -54 °C. The minimum acceptable flash point under an open flame as measured in an open cup test (ASTM D-92) is 246 °C. The oil must have a low deposit forming tendency at a bulk oil temperature of 200 °C in 100 hr bearing tests. The upper test temperature of 300 °C was chosen for the present study to evaluate the effectiveness of PS212 as a back-up lubricant during oxidative degradation of the liquid lubricant at a temperature beyond its oxidation threshold.

The plasma sprayed PS 212 coating has been described in detail (refs. 1, 2, and 5). Briefly, the nominal chemical composition by weight percent is: 70 metal bonded chromium carbide, 15 silver, and 15 barium fluoride/calcium fluoride eutectic. The coating is sprayed to a thickness of about 0.38 mm, then diamond ground to 0.25 mm.

Steel Slider Material

M50 bearing steel was chosen as the first pin and baseline disk material. This is a common bearing material used in gas turbine engines. It is noted for its high hardness and resistance to rolling contact fatigue. Composition by weight percent is: 0.85C, 4.10Cr, 4.25Mo, 1.0V, bal.Fe. The chromium molybdenum, and vanadium content of M50 are to improve hot hardness and temper resistance (ref. 6). Room temperature hardness is HRC 63. The maximum acceptable temperature for rolling element bearing applications is 315 °C, based on a minimum hot hardness of HRC 58 (ref. 7).

Super Alloy Slider Materials

The cobalt-base alloy Stellite 6B was chosen as a pin material because it is one of the more wear resistant alloys used for sliding contact components in turbines and other high temperature applications. Although not as hard as rolling element bearing metal, it is among the hardest of the super alloys. The nominal composition by weight percent is: 28-32Cr, 3.5-5.5W, 0.9-1.4C, 3Ni,2Si, 3Fe, bal. Co. Room temperature hardness is typically HRC 40. Substantial hardness is retained to high temperatures: HRC is about 28 at 427 °C (ref. 8).

Inconel X-750 was chosen as a disk material for baseline friction and wear studies of uncoated metal because it is a precipitation hardenable nickel base alloy. The room temperature hardness of the disks used in this study is HRC 35-38.

APPARATUS AND TEST PROCEDURE

The pin on disk tribometer is illustrated in figure 1. The specimens are mounted in an enclosed test chamber and the air humidity is controlled at a room temperature relative humidity of 50 percent. A stationary pin with a 4.76mm hemispherical radius is placed in sliding contact with the flat surface of a rotating disk under a normal load of 9.8N. Three consecutive wear tests generate three concentric wear tracks on each disk, thereby eliminating the need to refinish the disks after each test. The disks are thoroughly cleaned and wear is measured after each test. Each test is interrupted 5 or 6 times to allow measurements of pin wear scars so that the influence of run-in wear relative to steady state wear can be ascertained. Disk wear is measured only after the completion of each test. Disk rotation is always at 50 RPM and surface velocities at the wear track diameters are 7.1, 8.1, and 9.1 m/min (0.12, 0.14, and 0.15 m/s).

The load of 9.8N and the relatively low surface velocities chosen are based on previous parametric studies with an ester lubricant of similar viscometric properties. That study demonstrated the experimental conditions required for the pin on disk experiments to be in the boundary lubrication regime (ref. 9).

Friction and wear data are obtained in the absence of a lubricating oil, for comparison with friction and wear during boundary lubrication with a polyol ester oil qualified under the military specification MIL L-23699. During boundary lubrication tests, the disk is partially submerged in the test lubricant contained in a glass cup. The disk is heated with an induction coil. Disk temperature at the wear track diameter is monitored with an infrared pyrometer.

Wear is expressed in this paper as a wear factor that gives volumetric wear per unit load and sliding distance. Use of this factor for wear predictions assumes that wear is directly proportional to load and to sliding distance. This assumption is an oversimplification, but is valid for steady state wear after the initial run-in stage of wear is complete, and if the wear mechanism is the same in the wear test as it is in the application of interest. The wear factor units used in this paper are: $k = mm^3/Nm$

Pin wear is determined by measuring the wear scar diameter of the pin from 50X photomicrographs, then calculating the wear volume. The lower limit for accurate measurements is well below even the lowest pin wear observed in this program.

Disk wear is determined by recording several cross sections across the wear track with a stylus profilometer, computing the average wear area of the profiles, then multiplying by the track circumference to obtain the wear volume. Disk wear corresponding to a wear factor less than 10^{-6} for the load and sliding distances (Nm) used are reported as N.D. (not detectable) because lower wear could not be distinguished from the surface roughness topography.

METHOD OF DATA PRESENTATION

In most cases, three replicate tests are performed for each test condition in the experimental program. Friction is measured continuously, and sampled periodically for data presentation. The absolute range, the average, and the single standard deviations for the friction coefficients are then computed.

Each test is typically interrupted six times to measure cumulative pin wear for various sliding distance intervals from the beginning of the test. Cumulative wear factors, their average values and single standard deviations are then computed and compared to wear factors during the linear steady state segments of the wear process. This is done to estimate the magnitude of run-in wear compared to the total wear for various test times.

Run-in wear rates tend to be higher than steady state wear rates. Since run-in wear occurs early in the wear process, the percentage contribution of run-in wear to the cumulative wear becomes less with increasing test duration. Therefore steady state wear factor values tend to converge with the cumulative wear factors for long test durations.

Disk wear is measured only after the completion of each test. Therefore, run-in effects of the disks are not determined. Errors introduced by not taking run-in into account are positive in sign and therefore conservative in wear predictions.

EXPERIMENTAL RESULTS I

M50 Bearing Steel versus M50 and PS 212

Friction during dry sliding

Friction coefficients from room temperature to 300 °C are presented in table I(a). The arithmetic means and the single standard deviations, along with the data population used in the averaging are given. Bar graphs of the data are presented in figure 2.

At room temperature, sliding is rough and erratic for both material combinations. Stick-slip is less pronounced for M50/PS 212 than for M50/M50. The mean friction coefficient for M50/PS 212 is 0.53 compared to 0.61 for M50/M50. Occasional friction spikes occur that are much higher than indicated by the standard deviation values; therefore, the absolute ranges of friction coefficients are also given in table I(a).

At 300 °C, friction coefficients are much lower than at room temperature at 0.33±0.09 for M50/PS 212 and 0.35±0.05 for M50/M50. Less stick-slip occurs at the higher temperature for both material couples.

These baseline data show that friction is generally unfavorable for M50 on either itself or PS 212 under dry sliding conditions at low sliding velocities.

Wear during dry sliding

Disk wear and cumulative pin wear data are presented in table I(b) and figure 3. M50 pin wear factors for the two material pairs are seen to be within data scatter of each other. M50 disk wear factors are on the order of 10^{-5} mm^3/Nm at room temperature and 10^{-6} mm3/Nm at 300 °C. On the other hand, no wear at all is discernible by stylus profilometry on the PS 212-coated disks at either temperature.

Run-in effects; Plots of M50 pin wear versus sliding distance at 25 °C are presented in figure 4. The slopes and Y axis intercepts were calculated by least squares and are given in table I(c). The data points accurately fit the computed lines showing a direct proportionality of pin wear volume with sliding distance. The Y axis intercept values are small indicating very little run-in effect.

Plots of M50 pin wear versus sliding distance at 300 °C are presented in figure 5. Here a large but fairly reproducible run-in effect exists for M50/PS 212. Run-in of M50 on M50 is totally unpredictable with variations in duration from essentially zero to 200 meters of sliding for two tests and one test in which the run-in phase of high wear continues to the end of the 600 meter duration test.

Friction during boundary lubricated sliding

As might be expected, much lower friction is observed at 25 °C under boundary lubrication with the formulated ester than in dry sliding. Both material sliding combinations are effectively lubricated. The friction coefficients of M50/PS 212 are 0.15±0.01 and those of M50/M50 are 0.09±0.03.

At 300 °C, solid decomposition products of the oil deposit on the disk surfaces. Friction coefficients are higher than during dry sliding at this temperature. PS 212 is of no benefit in reducing friction during sliding against M50 under this test condition.

Wear during boundary lubricated sliding

Pin and disk cumulative wear factors under boundary lubrication conditions are presented in tables I(b) and figure 3. Steady state wear data are given in table I(c) and figures 6, 6(a), and 7. The bar graphs of figure 3 show that at 25 °C, the cumulative pin wear factors for boundary lubrication are substantially lower than for dry sliding, and M50 pin wear against PS 212 is on the average about 1/10 the wear against M50. No wear measurable by surface profilometry is detectable on either the M50 or the PS 212-coated disks.

Run-in effects during boundary lubricated sliding

Plots of pin wear versus sliding distance at 25 °C are presented in figure 6(a). Wear rates are higher for M50/M50 then for M50/PS 212. There is a pronounced run-in effect for M50/M50. This is possibly due to the time required for the antiwear additives in the oil to take effect. Run-in of M50/PS 212 is not obvious at the scale of this graph. The data are therefore replotted on an expanded Y axis in figure 6(b), and a run-in effect is now seen that persists out to about 1 km of sliding distance.

The average cumulative pin wear factor for M50/M50 is 3×10^{-6} mm^3/Nm, while average steady state wear factors are 1.4×10^{-7} mm^3/Nm with no measurable M50 disk wear. For M50/PS 212, the corresponding wear factors are 4×10^{-7} mm^{3}-/Nnm cumulative and 1.7×10^{-8} mm^3/Nm steady state with no measurable wear of the disk coating.

The steady state wear factors on the order of 10^{-8} mm^3/Nm for M50/PS 212 are considered to be very low. For example, Woydt and Habig report that wear factors of 5×10^{-8} mm^3/Nm or lower are needed to match the low wear of piston rings and cams during 2000 hr of operation in a conventionally oil lubricated internal combustion engine (ref. 10).

Oxidative degradation of the oil occurs during tests at 300 °C. Boundary lubrication is not achieved with either sliding material combination, and substantial deposits of oil decomposition products are formed on the disks. Pin wear is about the same as it is in dry sliding. However, no detectable disk wear occurs. It is possible that the deposits on the disks contribute to the absence of disk wear by effectively preventing direct metal to metal contact with the M50 pin. The least squares data and plots of pin wear versus sliding distance at 300 °C are presented in table I(c) and figure 7. The Y intercepts are small relative to the high wear rates. Therefore the cumulative and steady state wear factors are within data scatter of each other.

SUMMARY REMARKS

M50 Bearing Steel

The most apparent benefit derived from applying the PS 212 coating on the wear disks is improved wear resistance. No coating wear measurable by surface profilometry occurs during dry or oil-lubricated sliding of PS 212 against M50 bearing steel at room temperature or at 300 °C. M50 pin wear is within data scatter for dry sliding against uncoated compared to PS 212 coated disks. However, in the presence of the liquid lubricant, M50 pin wear factors are consistently lower against PS 212 than against uncoated M50. The lowest steady state pin wear factor for M50/M50 during boundary lubrication at 25 °C is 1.0×10^{-6} mm^3/Nm, compared to 2.0×10^{-8} mm^3/Nm for M50/PS 212

Unfortunately. the coating does not provide a similar benefit in reducing friction. Friction coefficients are within the large data scatter bands for M50/M50 and M50/PS212, but on the average, friction coefficients are higher for M50/PS 212.

EXPERIMENTAL RESULTS II

Stellite 6B versus Inconel X-750

Friction during dry sliding

Friction coefficients are presented in table II(a) and in figure 8. Friction coefficients at room temperature average about 0.54 for 6B versus uncoated and PS 212-coated Inconel-X-750. Sliding is very rough with broad band traces on the continuous friction force recordings. The high friction of PS 212 at room temperature and low sliding velocity has also been observed for sintered pins of PM 212 (the powder metallurgy version of PS 212) sliding against the nickel base alloy Rene 41 (ref. 11). However,that study also showed that friction coefficients decreases with increasing sliding velocity to about 0.4 at 1m/s and about 0.35 at 2.7 m/s. Contact configuration also has an influence on friction. During low speed oscillating tests of PM 212 cylindrical bushings, friction coefficients averaged 0.35 at room temperature. and were 0,24 from 200 °C to 700 °C (ref. 12). The lower friction for the bearings may be associated with the high conformity in the bearing sliding contact area compared to the counterformal nature of the pin on disk contact.

Wear during dry sliding

Cumulative pin and disk wear data are presented in table II(b) and in figure 9. At room temperature, 6B pin wear against PS 212 is about 1/4 that of uncoated Inconel X-750. The average wear factor for uncoated Inconel X-750 disks is 9.9×10^{-4} mm^3/Nm. It is an order of magnitude lower for PS 212-coated disks at 6.3×10^{-5} mm^3/Nm.

Run-in effects

Steady state pin wear factors and least squares data are given in table II(c). Wear versus sliding distance is plotted in figure 10. The data fit the calculated straight line fit from the beginning of the tests. Cumulative compared with steady state wear factors are within data scatter. Therefore run-in effects are negligible.

Friction during boundary lubricated sliding

Friction data are presented in table II(a). Friction coefficients from room temperature to 300 °C are plotted in figure 8. They are all within the range expected for boundary lubrication. Sliding is smoother against the coated disks, but friction is consistently higher than it is for then coated disks.

Wear during boundary lubricated sliding

Cumulative wear factors are presented in table II(c) and figure 9. Pin wear factors for the coated and uncoated disks are within data scatter of each other at all four temperatures from 25 to 300 °C. At 25 °C, wear is not detectable on the uncoated disks, and the average wear factor is E-5 for PS 212. At 100 °C, the average wear factor for the uncoated disks is not detectable ($k < 10^{-6}$ mm^3/Nm); The average wear factor for PS 212-coated disks is 2.6×10^{-5} mm^3/Nm. At 200 and 300 °C, there is no measurable wear on the PS 212 coatings, while the wear factors average 4.8E-5 and 1.3×10^{-4} mm^3/Nm respectively for the uncoated disks.

Run in effects

Steady state pin wear data and least squares results are presented in table II(c). The fit of the experimental data to the calculated straight lines are shown in figures 11 to 14. At 25 °C, the steady state wear rates of the 6B pins are about the same against coated or uncoated disks. However, there is a much more pronounced run in effect on the wear of pins sliding against the uncoated disks that accounts for their higher cumulative wear factors shown in figure 9.

At 100 and 200 °C, no significant run-in effects are noted. All pin wear rates are constant, and within data scatter for pinstested against coated or uncoated disks. At 300 °C, some pin wear rates against uncoated Inconel X-750 vary erratically with sliding distance, which is not surprising because degradation products of the oil deposit on the disks during testing at this temperature.

SUMMARY REMARKS

Turbine Alloys

As in the case of M50 tool steel, the primary benefit of coating the Inconel X-750 disks with PS 212 is the very low wear of the coating under boundary lubrication sliding conditions. Friction coefficients of the lubricated specimens are higher for sliding against the coated disks, but within the expected range for boundary lubrication from 25 to 300 °C. This is different than the results for M50 for which low friction of coated or uncoated disks is also low at room temperature, but is very high at 300 °C.

CONCLUDING REMARKS

The objective of this program was to determine whether the PS 212 coating is beneficial as a back-up lubricant for M50 bearing steel and for the cobalt alloy Stellite 6B under boundary lubrication conditions with a synthetic oil qualified under the turbine engine oil specification MIL L 23699D. Tribotests in the M50 series were conducted at 25 and 300 °C, and in the 6B series at 25, 100, 200, and 300 °C. The MIL spec requires low deposits at a bulk oil temperature of 200 °C, but oxidative degradation of the oil is to be expected at 300 °C. The results of the tribotests led us to the following conclusions:

1. In general, there are benefits to using PS 212 as a back-up lubricant for M50 and 6B under conditions of marginal lubrication with the turbine engine oil. They are:

(a) Lower wear of M50 under boundary lubrication conditions; M50 pin wear in room temperature tests is an order of magnitude higher against M50 disks than against PS 212-coated disks. At 300 °C, on the average, pin wear is about three times higher against the uncoated disks. Oil degradation products are deposited on the disks during the 300 °C tests. No wear is detected by surface profilometry of either the M50 or the PS 212-coated disks.

(b) Lower wear of PS 212-coated disks compared to uncoated Inconel-X disks sliding against 6B pins at elevated temperature; there was no detectable wear on the PS 212-coated disks tested at 200 and 300 °C, while for uncoated Inconel X-750 disks,wear was moderate at 200 °C and high at 300 °C.

2. Limitation of PS 212 as a back-up lubricant for turbine oil;

There was no reduction in friction coefficient when the disks were coated with PS 212. At room temperature, the average friction coefficient of M50 against PS 212 was 0.15 and against M50, it was 0.10; at 300 °C, friction coefficients exceeded 0.5 for both wear couples. In the 6B series, friction coefficients were below 0.2 from room temperature to 300 °C for both wear couples, but was always higher for the coated disks.

3. On balance, it appears to be advantageous for wear control to use the PS212 coating as a back-up lubricant to turbine engine oils under sliding conditions, especially if temperature excursions beyond the thermal capabilities of the oil occur.

REFERENCES

1. DellaCorte, C. and Sliney, H. E., "Composition Optimization of Self-Lubricating Chromium Carbide-Based Composite Coatings for Use to 760 °C" ASLE Trans. 30, 77-83, 1987.

2. Sliney, H. E., "Coatings for High-Temperature Bearings and Seals", NASA TM 100249, DOE/NASA/50112-71, 1987.

3. Haggerty, James J. "Engine Lubricants", Spinoff 1993, NASA, ISBN 0-16-042100-4, US Govt Printing Office, Wash. DC.

4. Specification: "Lubricating Oil, Aircraft Turbine Engine, Synthetic Base, MIL-L-23699D, 1990, Naval Air Systems Command, Air 53632, Wash. DC.

5. DellaCorte, C. and Sliney, H. E., "The Effects of Atmosphere on the Tribological Properties of a Chromium Carbide-Based Coating for Use to 760 °C", Lubr. Engr. 44, 338-344, 1988.

6. Burrier, Harold, Jr., "Bearing Steels", ASM Handbook, 1, 10th Edition, pp 380-388, Properties and Selection: Irons, Steels, and High-Performance Alloys, Lampman, S. R., Techn. Ed., Materials Park, Ohio, 1990.

7. Moyer, C. A., "Friction and Wear of Bearing Steels" ASM Handbook, 18, pp 725-733, Friction, Lubrication, and Wear Technology, Henry, S. D. ,Ed., Materials Park, Ohio, 1992.

8. Crook, P., "Friction and Wear of Cobalt-Base Wrought Alloys", IBID, pp 765-771.

9. Loomis, W. R. "Steady State Wear and Friction in Boundary Lubrication Studies", NASA T.P. 1658, May, 1980.

10. Woydt, M. and Habig, K. H., "Tribological Criteria and Assessment for the Life of Unlubricated Engines", Lubr. Engr. 50, 519-522, 1994.

11. DellaCorte, C. and Sliney, H. E., "Tribological Properties of PM 212", Lubr. Engr., 47, 298-303, 1991.

12. Sliney, H. E., "Test Results to 700 °C for Cylindrical PM 212 Bearings", pp IV-27 to 43, Proceedings of the 1992 Coatings for Advanced Heat Engines Workshop, Sponsored by Office of Transportation Technology, US Dept of Energy, Monterey, Ca. Aug.3-6, 1992.

TABLE I(a).—FRICTION OF M50 TOOL STEEL AGAINST ITSELF COMPARED TO M50 AGAINST PS 212 UNLUBRICATED AND LUBRICATED WITH MIL-L-23699 TURBINE ENGINE OIL

[Test conditions: Room Air, M50 pins of 4.76 mm radius 9.8 N load, 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm variable durations of 60 to 660 min]

Sliding materials pin/disk	Test temperature, °C	Lubricant	Coefficient of friction		Stick-slip characteristic[b]
			Range min-max	Statistics[a] $\bar{x}$ σ (n)	
M50/M50	25	Dry	0.55 to 0.75	0.61±0.12 (6)	5
M50/M50	300	↓	.30 to .45	.39±.05 (13)	4
M50/PS212	25	↓	.45 to .80	.53±.13 (11)	3 to 4
M50/PS212	300	↓	.25 to .50	.33±.09 (13)	2 to 4
M50/50	25	Mil-L23699 polyol ester	0.08 to 0.13	0.09±0.03 (24)	3
M50/50	300	↓	.49 to .56	.52±.11 (10)	5
M50/PS212	25	↓	.14 to .16	.15±.01 (25)	1
M50/PS212	300	↓	.44 to .70	.60±.09 (8)	5

[a]$\bar{x}$ = arithmetic mean σ = one standard deviation (n) = number of data points.

[b]1 = very smooth sliding; 2 = smooth; 3 = moderately rough; 4 = rough; and 5 = very rough.

TABLE I(b).—AVERAGED CUMULATIVE WEAR[(a)] OF M50 TOOL STEEL AGAINST ITSELF COMPARED TO M50 TOOL STEEL AGAINST PS212 UNLUBRICATED AND LUBRICATED WITH MIL-L 23699 TURBINE ENGINE OIL

[Test conditions: Room Air, M50 pins of 4.76 mm radius 9.8 N load, 7.1, 8,1, and 9.1 m/min sliding velocity at 50 rpm variable durations of 2 to 660 min]

Sliding materials pin/disk	Test temperature, °C	Lubricant	Wear factors, mm^3/Nm [$\bar{x}$ σn-1 (n)][b]	
			Pin $K_p \times 10^5$	Disk $K_p \times 10^5$
M50/M50	25	Dry	1.0 to 0.2 (17)	1.7±0.5 (3)
M50/M50	300	↓	3.5 to 2.4 (9)	0.2±0.2 (3)
M50/PS212	25	↓	1.3 to 0.2 (16)	N.D.[c]
M50/PS212	300	↓	4.75 to 1.9 (12)	N.D.[c]
M50/50	25	Mil-L23699 oil	0.4±0.2 (24)	N.D.[c]
M50/50	300	↓	4.5±1.2 (13)	↓
M50/PS212	25	↓	0.034±0.028 (25)	↓
M50/PS212	300	↓	1.7±0.4 (16)	↓

[a]Includes run-in wear.

[b]$\bar{x}$ = arithmetic mean σ = one standard deviation (n) = number of data points.

[c]ND = No detectable wear by surface prokilometry.

TABLE I.(c).—STEADY STATE (S.S.) WEAR RATES OF M50 STEEL PINS 7-1, 8-1, AND 9-1 M/MIN AT 50 RPM, 8.8n LOAD, AIR ATM

	Test number	Disk temperature, °C	Slope, m^3/m	Y intercept, m^3	Square of correlation coefficient, R^2	SS wear factor, mm^3/Nm	Average SS wear factor, mm^3/Nm
Dry							
M50 Pins/M50 disks	1	25	0.078×10^{-12}	1.29×10^{12}	0.992	0.78×10^{-5}	0.97×10^{-5}
	2	25	.122	2.45	.987	1.20	
	3	25	.094	3.94	.999	0.94	
	4	300	.026	−3.23	.822	.26	$.26\times10^{-5}$
	5	300	.025	54.0	.799	.25	
	6	300	.543	10.1	.997	5.40*	-------
M50 Pins/PS 212 coated disks	7	25	0.119×10^{-12}	0.779×10^{-12}	0.999	1.20×10^{-5}	1.25×10^{-5}
	8	25	.163	−0.968	.999	1.60	
	9	25	.096	4.55	.994	0.96	
	10	300	.217	59.7	.999	2.20	1.16×10^{-5}
	11	300	.110	82.1	.968	1.10	
	12	300	.350	79.8	.982	3.50	
Lubricated with MIL L-23699 Polyol Ester							
M50 Pins/M50 disks	13	25	0.0182×10^{-12}	27.0×10^{-12}	0.975	0.18×10^{-5}	0.14×10^{-5}
	14	25	.0129	29.5	.987	.13	
	15	25	.0098	44.9	.964	.10	
	16	300	.405	6.00	.996	4.10	4.95×10^{-5}
	17	300	.580	5.46	.998	5.80	
M50 Pins/PS 212 coated disks	19	25	0.0002×10^{-12}	2.38×10^{-12}	0.999	0.002×10^{-5}	0.004×10^{-5}
	20	25	.0005	2.52	.999	.005	
	21	25	.0005	2 16	.971	.005	
	22	300	.125	34.0	.986	1.30	1.65×10^{-5}
	23	300	.199	3.46	.995	2.0	

*Author.

TABLE II(a).—FRICTION OF STAELLITE 6B AGAINST INCO X-750 COMPARED TO 6B AGAINST PS 212 UNLUBRICATED AND LUBRICATED WITH MIL-L 23699 GAS TURBINE ENGINE OIL

[Test conditions: Air, 4.76mm radius 6B pins; 9.8N load; 7.1, 8.1, and 9.1 m/min, sliding velocity (50 rpm) variable duration; 60 to 1020 min.]

Slidng materials, pin/disk	Test temperature, °C	Lubricant	Coefficient of friction		Stick-slip characteristic[b]
			Range, min/max	Statistics,[a] $\bar{x}$ σ (n)	
6B/I-X750	25	Dry	0.42 to 0.66	0.54±0.07(14)	5
6B/PS 212	25	Dry	.042 to .62	.54±.04 (12)	5
6B/I750	25	MIL-L 23699	0.2 to .09	.05±.02 (27)	2 to 3
6B/I750	100	Polyol ester	.07 to .09	.08±.01 (19)	3
6B/I750	200	↓	.13 to .15	.14±.01 (20)	3
6B/I750	300	↓	.14 to .19	.18±.01 (20)	5
6B/PS 212	25	↓	.09 to .14	.12±.01 (24)	2
6B/PS 212	100	↓	14. to .16	.15±01 (17)	2
6B/PS 212	200	↓	.15 to .21	.18±.02 (18)	2 to 3
6B/PS 212	300	↓	.14 to .22	.19±.02 (19)	1

[a] $\bar{x}$ = arithmetic mean; σ = one std deviation; (n) = number of data points.

[b] 1 = very smooth; 2 = smooth; 3 = moderately rough; 4 = rough; and 5 = very rough.

TABLE II(b).—CUMULATIVE WEAR FACTORS FOR 6B/INCONEL X-750 AND 6B/PS 212 COATINGS UNLUBRICATED AND LUBRICATED WITH MIL L-23699 TURBINE ENGINE OIL COMPARED TO 6B AGIANST PS 212 UNLUBRICATED AND LUBRICATED WITH MIL-L 23699 GAS TURBINE ENGINE OIL

[Test conditions: Air, 4.76mm radius 6B pins; 9.8N load; 7.1, 8.1, and 9.1 m/min, sliding velocity (50 rpm) variable duration; 60 to 1020 min.]

Slidng materials, pin/disk	Test temperature, °C	Lubricant	Wear factors, mm^3/Nm [$\bar{x}$ σ (n)]	
			Pin, $Kp \times 10^5$	Disk, $Kd \times 10^5$
6B/I-X750	25	Dry	4.1±1.3 (15)	99±55 (13)
6B/PS 212	25	Dry	1.0±0.2 (12)	6.3±2.4 (4)
6B/I750	25	MIL-L 23699	0.19±0.15 (24)	ND[c]
6B/I750	100	Oil	.08±.04 (19)	ND[c]
6B/I750	200		.03±.02(13)	4.8±2.0 (3)
6B/I750	300		.05±.03 (13)	12.9±6.7 (4)
6B/PS 212	25		.07±.05 (25)	0.9±0.2 (2)
6B/PS 212	100		.06±.02 (18)	2.6±1.2 (3)
6B/PS 212	200		.06±.01 (18)	ND[c]
6B/PS 212	300		.09±.03 (19)	ND[c]

[b] $\bar{x}$ = arithmetic mean; σ = one std deviation; (n) = number of data points.

[c] ND = No detectable wear by surface profilometry.

TABLE II.(c).—STEADY STATE WEAR RATES OF 6B PINS BY LEAST SQUARES CALCULATIONS 7.1, 8.1, AND 9.1 m/s AT 50 rpm, 9.8N LOAD, AIR ATMOSPHERES

	Test number	Disk temperature, °C	Slope,[a] m^3/m	Y intercept,[b] m^3	Square of correlation coefficient, R^2	Wear factor, mm^3/Nm
Dry Sliding						
6B Pins/Inconel X-750 Disks	1	25	0.206×10^{-12}	7.62×10^{12}	0.899	2.1×10^{-5}
	2	25	.451	1.23	.984	4.5
	3	25	.576	−15.0	.997	5.8
6B Pins/PS 212 coated disks	4	25	0.111	0.93	0.995	1.1
	5	25	.087	1.05	.999	0.9
Boundary Lubricatel With MIL L-23699						
6B Pins/Inconel X-750	6	25	0.0014×10^{-12}	9.80×10^{-12}	0.895	0.014×10^{-5}
	7	25	.0010	18.6	.950	.010
	8	25	.0017	13.5	.981	.017
	9	100	.0037	1.48	.997	.04
	10	100	.0039	0.99	.999	.04
	11	100	.0071	1.86	.973	.07
	12	200	.0005	.59	.973	.005
	13	200	.0005	1.13	.970	.005
	14	300	.0019	.44	.796	.02
	15	300	.0033	7.50	.913	.03
6B Pins/PS 212 coated disks	16	25	0.0002×10^{-12}	0.83×10^{-12}	0.982	0.002×10^{-5}
	17	25	.0009	2.55	.967	.01
	18	25	.0019	1.69	.999	.05
	19	100	.0054	0.76	.995	.05
	20	100	.0038	.36	.997	.04
	21	100	.0031	.19	.999	.03
	22	200	.0035	.04	.998	.04
	23	200	.0057	.25	.997	.06
	24	200	.0042	.69	.998	.04
	25	300	.00662	.73	.991	.06
	26	300	.0111	.82	.995	.11
	27	300	.0097	.74	.999	.10

[a]Calculated slope of wear volume versus sliding distance.

[b]Intercept of linear segment (Steady State Wear) of wear volume versus sliding distance.

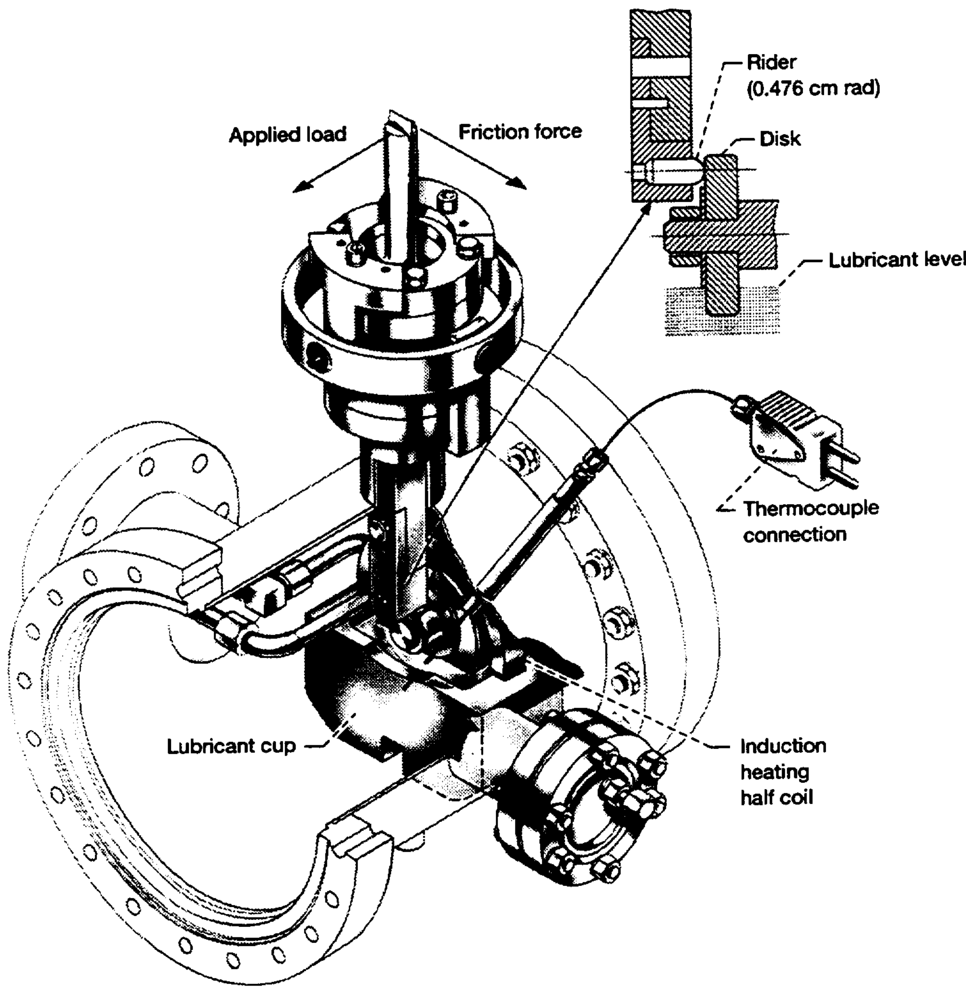

Figure 1.—Friction and wear apparatus.

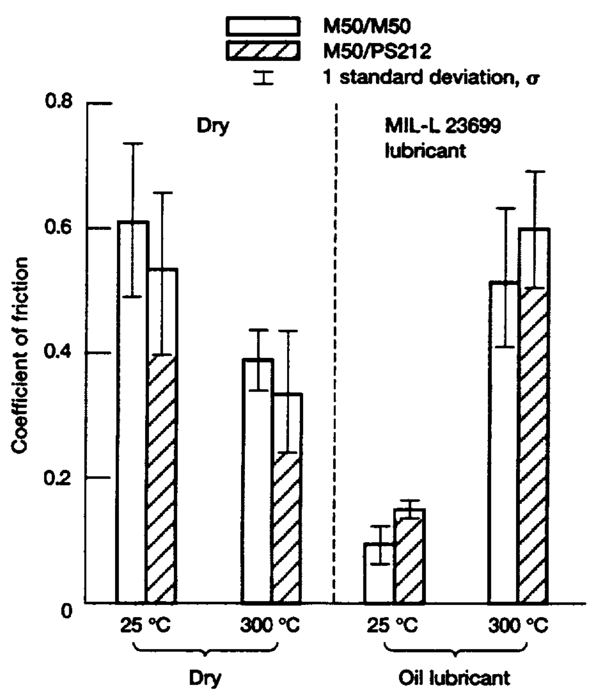

Figure 2.—Friction of M50 tool steel vs. itself and against PS212 dry and when lubricated with MIL-L 23699 polyol ester oil. 9.8 N load on M50 pins with 4.76 mm radius hemispherical tip, 8.1 ± 1 m/min sliding velocity.

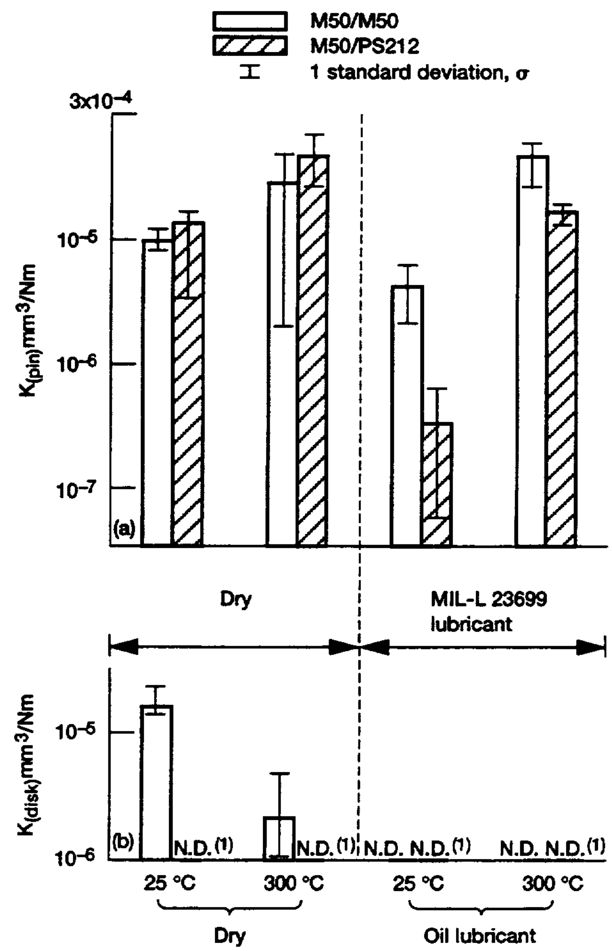

Figure 3.—Pin and disk cumulative wear factors (run in wear included) for M50 vs. M50 and M50 vs. PS212 dry and lubricated with MIL-L 23699 oil. (a) Pin wear. (b) Disk wear (1) No detectable wear by surface profilometry.

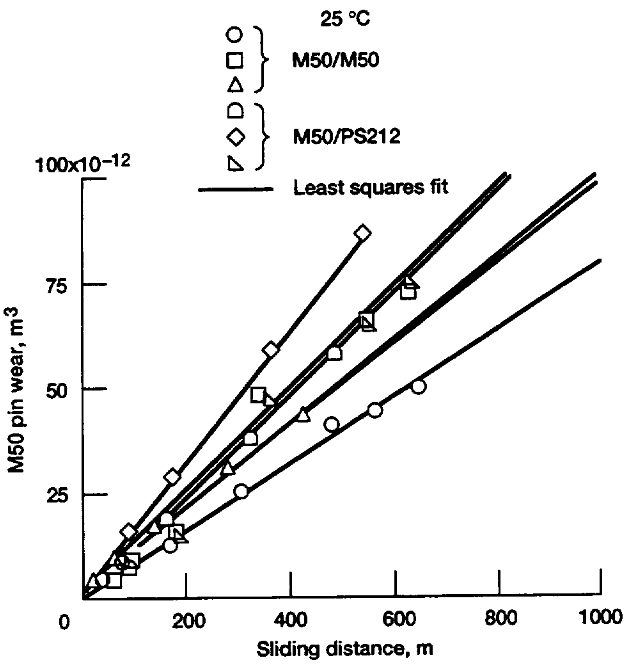

Figure 4.—Wear under dry sliding conditions at 25 °C of M50 pins against M50 disks and PS212-coated disks; 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere.

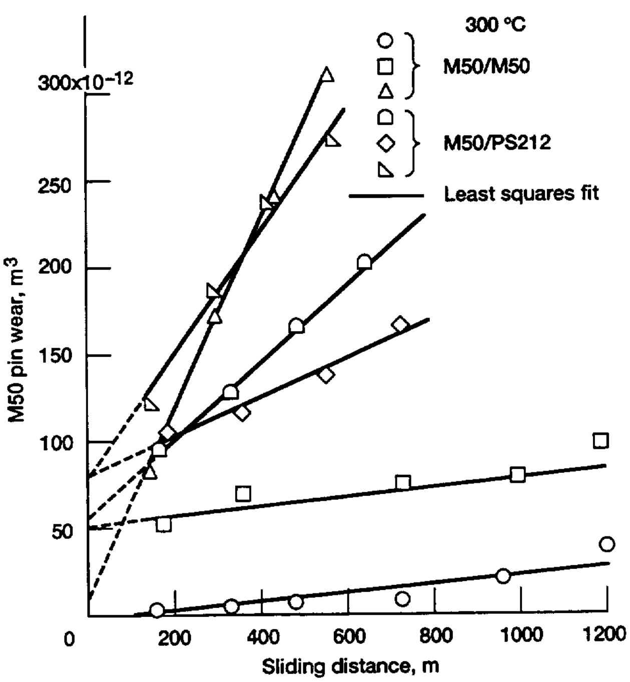

Figure 5.—Wear under dry sliding conditions at 300 °C of M50 pins sliding against M50 disks and PS212-coated disks; 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere.

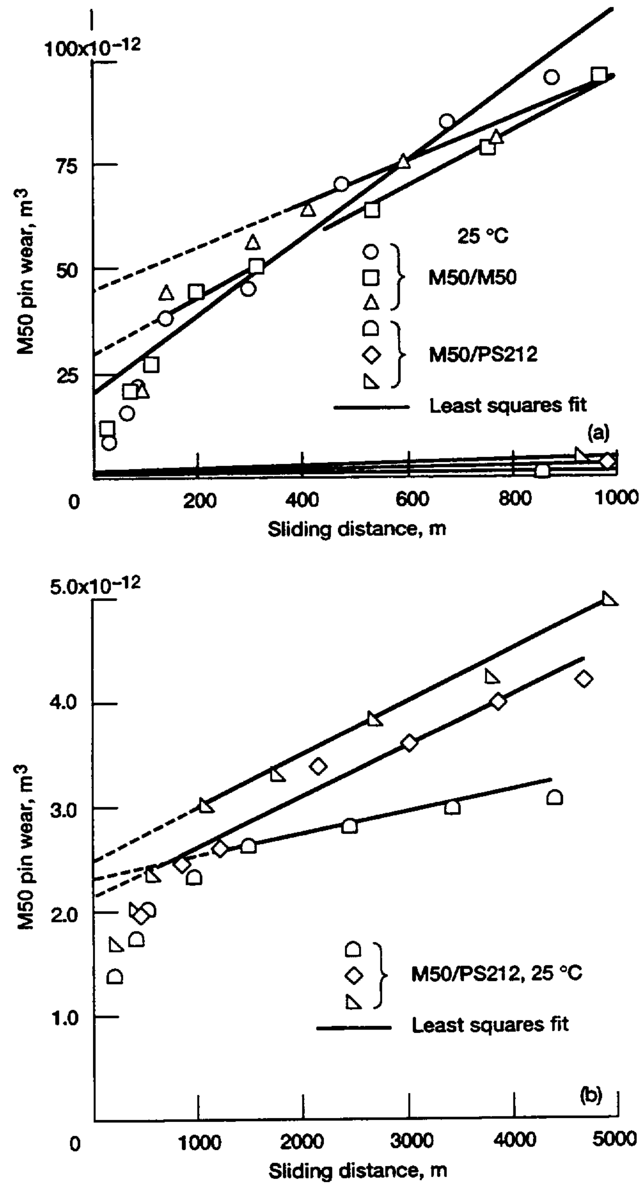

Figure 6.—(a) Wear at 25 °C of boundary lubricated M50 pins sliding on uncoated M50 disks and PS212-coated disks; MIL-L 23699 polyol ester lubricant 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere. (b). Expanded y axis.

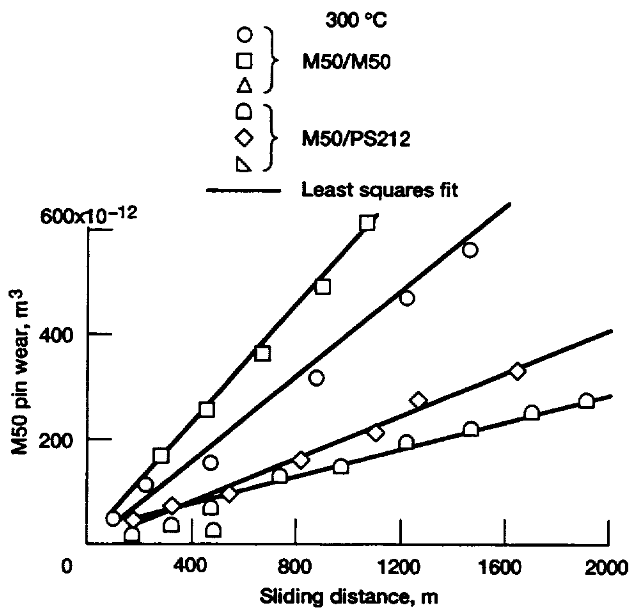

Figure 7.—Wear at 300 °C of boundary lubricated M50 pins sliding on M50 disks and on PS212-coated disks, MIL-L 23699 polyol ester lubricant; 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere.

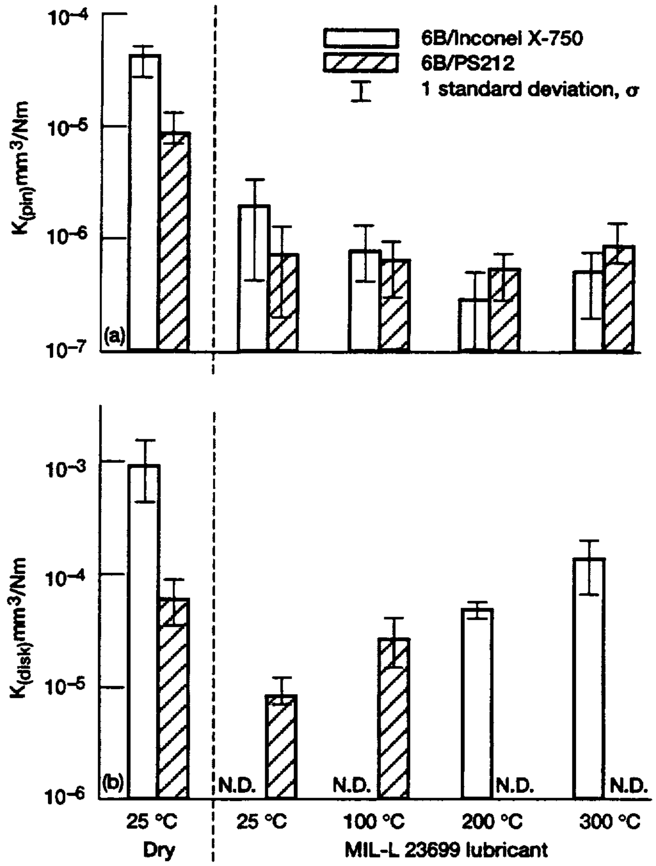

Figure 9.—Pin and disk wear factors for Stellite 6B vs. Inconel X-750 and 6B vs. PS212 dry and lubricated with MIL-L 23699 oil.

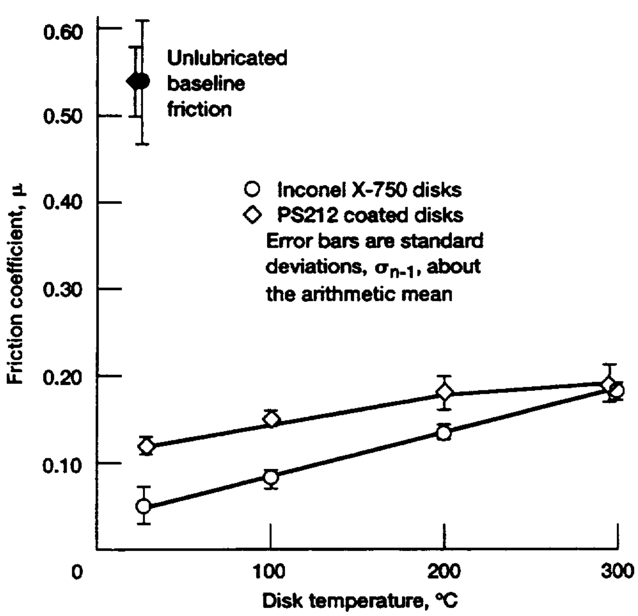

Figure 8.—Friction of Stellite 6B vs. Inconel X-750 and PS212 when lubricated with MIL-L 23699 polyol ester oil 9.8 N load on 6B pins with 4.76 mm radius hemispherical tip, 8.1 ± 1 m/min sliding velocity.

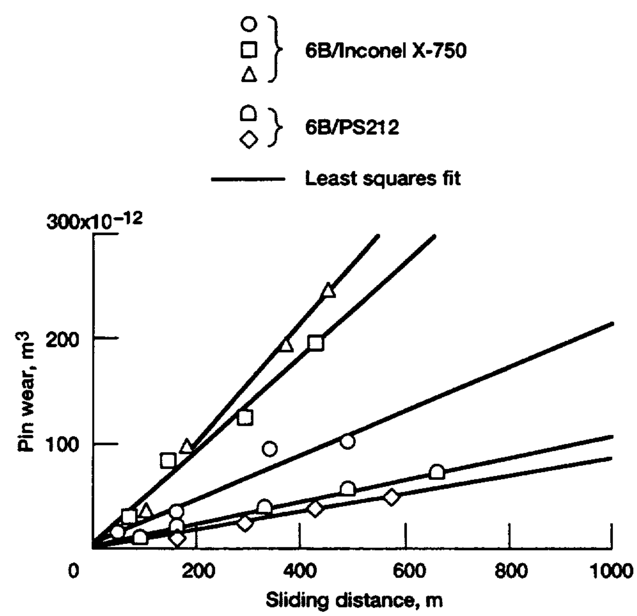

Figure 10.—Wear under dry sliding conditions at 25 °C of Stellite 6B pins against uncoated and PS212-coated Inconel X-750; 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere.

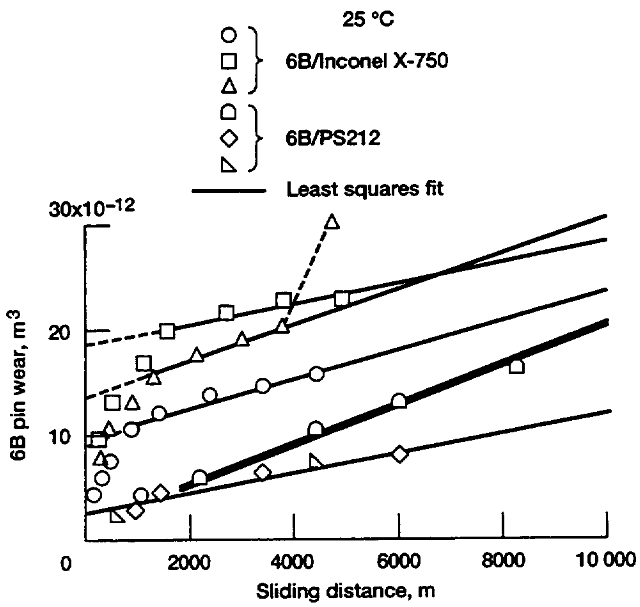

Figure 11.—Wear at 25 °C of boundary lubricated Stellite 6B pins sliding on uncoated and PS212 coated Inconel X-750; MIL-L 23699 polyol ester lubricant; 7.1, 8.1, and 9.1 m/min sliding velocity at 50 rpm; 9.8 N load; air atmosphere.

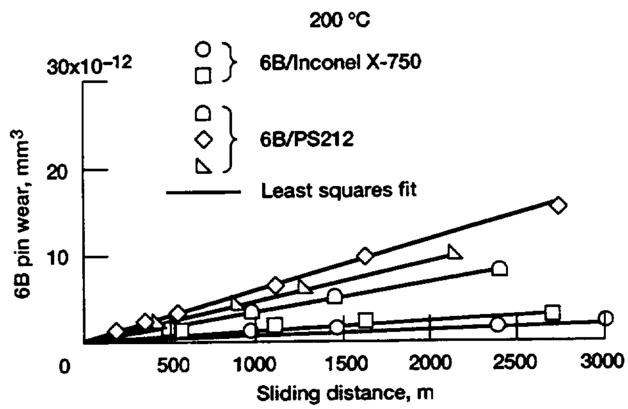

Figure 13.—Wear at 200 °C of boundary lubricated Stellite 6B pins sliding on uncoated and PS212-coated Inconel X-750; MIL L-23699 polyol ester lubricant; 8.1 ± 1 m/min sliding velocity; 9.8 N load; air atmosphere.

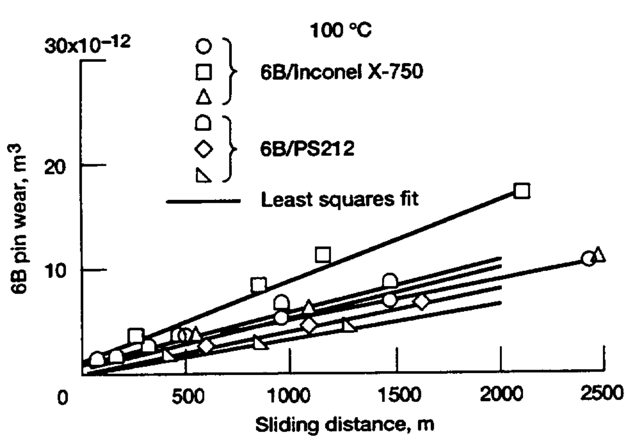

Figure 12.—Wear at 100 °C of boundary lubricated 6B pins sliding on uncoated and PS212-coated Inconel X-750; MIL L-23699 polyol ester lubricant; 8.1 ± 1 m/min sliding velocity, 9.8 N load; air atmosphere.

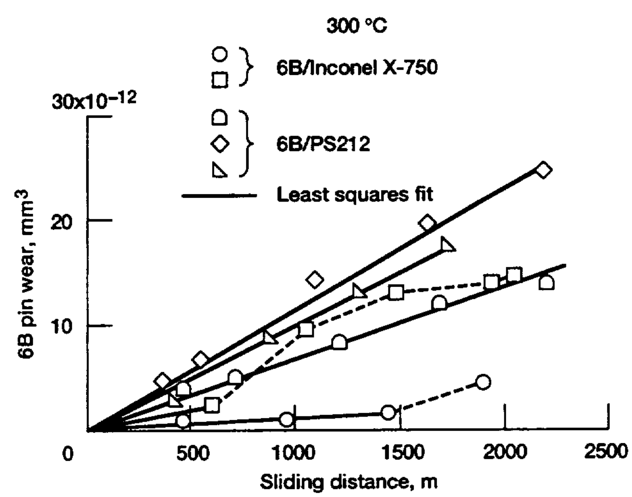

Figure 14.—Wear at 300 °C of boundary lubricated Stellite 6B sliding on uncoated and PS212-coated Inconel X-750; MIL L-23699 polyol ester lubricant; 8.1 ± 1 m/min sliding velocity, 9.8 N load; air atmosphere.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1994	Technical Memorandum

4. TITLE AND SUBTITLE

Evaluation of PS 212 Coatings Under Boundary Lubrication Conditions With an Ester-Based Oil to 300 °C

5. FUNDING NUMBERS

WU–505–63–5A

6. AUTHOR(S)

Harold E. Sliney, William R. Loomis, and Christopher DellaCorte

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9206

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106763

11. SUPPLEMENTARY NOTES

Prepared for the International Conference on Metallurgical Coatings and Thin Films sponsored by the American Vacuum Society, San Diego, California, April 24–25, 1995. Harold E. Sliney, Aerospace Design & Fabrication, Inc., 3003 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–25767); William R. Loomis and Christopher DellaCorte, NASA Lewis Research Center. Responsible person, Christopher DellaCorte, organization code 5140, (216) 433–6056.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unclassified - Unlimited Subject Category 23	

13. ABSTRACT (*Maximum 200 words*)

High friction and wear of turbine engine components occur during high temperature excursions above the oxidation threshold of the liquid lubricant. This paper reports on research to study the use of a high temperature self lubricating coating, PS 212 for back-up lubrication in the event of failure of the liquid lubricant. Pin on disk tests were performed under dry and boundary-lubricated conditions at disk temperatures up to 300°C. The liquid lubricant was a formulated polyol ester qualified under MIL L-23699. At test temperatures above the oil's thermal degradation level, the use of PS 212 reduced wear, providing a back-up lubricant effect.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
Solid lubricant; Boundary lubrication; Back-up lube coating; PS 212 carbide/fluoride lube coating	19	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	